An Experimental Study of Methods for Mitigating Blast and Fragment Hazards from a Large Exploding Tank

by

Charles J. Oswald, Wilfred Baker Engineering, Inc.
Darrell D. Barker, Wilfred Baker Engineering, Inc.

Methods for mitigating blast pressures and fragments from a large steel tank filled with 630 lbs of Otto fuel were investigated experimentally. Methods for mitigating the debris threat caused by the breakup of a reinforced concrete bay that housed the fuel tank were also investigated. The Otto fuel was assumed to have a TNT equivalency of 1.0. Several mitigation techniques were investigated during a one-fifth scale test series including: sand fill around the Otto fuel tank and concrete bay, a steel plate catch system for fragments and debris, a high strength fiber wrap on the walls of the bay, and blasting mats around the bay. All the concepts included some amount of sand fill around the tank. Substantial reductions in blast overpressure hazards were measured in all cases, but concrete debris throw distances were not reduced to acceptable distances. A case where the fuel tank was located in a large sand berm outside the bay was modeled in a subsequent one-third scale test series and acceptable reductions in both blast overpressure and fragment hazards were measured. The reduction in the peak pressure and impulse measured during both test series was found to be a function of the scaled radius of the sand placed around the charge and scaled standoff distance.

Background

A number of blast and fragment mitigation concepts were investigated experimentally as part of a project to develop a suppression system for a large storage tank filled with Otto fuel. It is a relatively stable mono-propellant used to power torpedo motors. This fuel is classified as a Group 1 propellant by NAVSEA-OP-5, and, therefore, relatively short separation distances are required between stored quantities of the fuel and other operations. However, recent events, including a 1995 Otto fuel explosion during torpedo testing, have caused plants performing this type of testing to evaluate the potential hazards from a large Otto fuel detonation and develop methods to mitigate the hazards. In one case that was investigated by Wilfred Baker Engineering, Inc. (WBE), an Otto fuel tank with a maximum stored quantity of 630 lbs of fuel was located approximately 40 ft from an occupied control building. An administration building was located approximately 600 ft away with a large quantity of glass on the wall facing the potential explosion site (PES). Since plant personnel were concerned about an accidental detonation of the fuel and they did not want to move their testing operations unless it was absolutely necessary, a project was initiated to develop a suppression system that would mitigate the potential hazards from a detonation of the fuel to acceptable levels.

The fuel was stored in a 2 ft diameter by 4 ft high steel pressure vessel with 1-5/16 inch thick walls. The fuel tank was housed in a relatively small reinforced concrete bay. The walls for the bay were 12 inches thick and the roof was 6 inches thick, with minimal attachment to the walls. One wall was constructed with a frangible material that was designed to vent potential gas

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1996**	2. REPORT TYPE	3. DATES COVERED **00-00-1996 to 00-00-1996**
4. TITLE AND SUBTITLE **An Experimental Study of Methods for Mitigating Blast and Fragment Hazards from a Large Exploding Tank**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Wilfred Baker Engineering, Inc,8700 Crownhill Blvd,San Antonio ,TX,78209-1128**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM000767. Proceedings of the Twenty-Seventh DoD Explosives Safety Seminar Held in Las Vegas, NV on 22-26 August 1996.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**17**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

pressures to the exterior of the facility. There was also a reinforced concrete wall in place directly opposite of the frangible wall to trap any escaping fragments. Figure 1 shows a layout of the fuel tank and surrounding reinforced concrete bay. The fuel tank could be moved to another location in the bay, or to a nearby location outside the bay as part of any modifications to reduce hazards from an Otto fuel detonation.

An analysis of the consequences from the design basis accident (DBA), assuming that 630 lb of Otto fuel detonated with a TNT equivalency of 1.0, indicated that blast overpressures were sufficient to collapse the relatively light weight roof of the control room. The analysis also indicated that overpressures at the administration building were sufficient to fail the glass and some of the relatively light structural components on the exterior face. Additionally, a parking lot located approximately 200 ft from the PES accommodated a large number of cars, which the client wanted to protect from the effects of a potential accidental explosion.

Table 1 summarizes the blast hazard at these areas from the DBA. The permissible blast pressure on the control room and parking lot are based on DoD explosive safety criteria[1]. The permissible peak pressure on the administration building windows is the estimated peak pressure of a long duration blast pulse that would cause window breakage. As Table 1 shows, a very large near-field pressure reduction and a far-field pressure reduction of approximately two were needed. All pressures are free-field pressures except as noted in the table.

Table 1. Blast Hazard from Otto Fuel Detonation

Affected Area	Distance (ft)	Peak Predicted Blast Pressure (psi)	Permissible Blast Pressure (psi)	Criteria
Control Room	38	55	2.3	DoD Criteria for Remote Operations (K=24)
Parking Lot	215	2.2	1.2	DoD Criteria for Inhabited Buildings (K=40)
Administration Building	625	1.1 (reflected)	0.5 (reflected)	Window Breakage

The parking lot and administration building also require protection from hazardous debris according to the DoD explosive safety criteria. The debris hazard was studied using the DISPRE model[2] and hazardous densities of reinforced concrete debris from the fuel cell bay walls were calculated at distances greater than 1250 ft. Therefore, neither the parking lot, nor the administration building were provided with fragment protection required by DoD safety criteria. Also, calculations showed that primary fragments from the steel fuel tank could perforate through the concrete walls and roof of the fuel cell bay and add to the fragment hazard. The initial velocity of primary fragments from the sidewall of the steel tank was calculated to be 5500 ft/sec with the Gurney equation, assuming that Otto fuel was equivalent to TNT. The largest calculated fragment mass at the 99% confidence level was 1.8 lbs. Fragment calculations were made using the procedures in TM5-1300[3].

Mitigation Concepts

This situation presented a significant challenge since the consequences of an accidental explosion had to be contained within the confines of a relatively small area. When it was determined that mitigation of the hazards would be required, several conceptual designs were developed with the goal of keeping the storage tank in the existing bay. The mitigation solution had to limit overpressures as well as contain fragments and debris within an area near the test cell.

As a first step, available mitigation techniques were reviewed. Significant pressure reductions have been observed for cases where the charge is covered by a dense material, including ductile steel casing on bombs, and both water cover and soil cover over explosives. The material covering the charge absorbs some of the energy created by the explosion, thereby reducing the net energy in the shock wave. Suppressive shields have also been used to reduce external blast pressures[4]. The shield surrounds the explosive, so that the shock wave must pass through narrow openings between overlapping steel shapes in the walls of the shield. This action reduces blast pressures in the surrounding area. Blasting mats manufactured by weaving steel wire rope into mats have been observed to reduce blast pressures in a manner similar to suppressive shields[5].

These mitigation concepts also reduce primary fragment hazards. Water and soil cover slow down primary fragments so that they are thrown a shorter distance. Suppressive shields are usually designed to stop all primary fragments by sizing the thickness of the steel shapes to stop the fragments. Blasting mats do not necessarily stop all fragments, since there are usually lines-of-sight through the weave in the mats at various angles off the horizontal. However, the mats stop most of the fragments, particularly larger fragments. A final concept that was considered for controlling building debris was placement of ductile or high strength material on the external face of the building walls. This material would either contain the building debris, or absorb a significant amount of energy from the applied blast pressures and reduce the initial velocity of building debris.

Several possible modifications to the fuel cell bay were developed based on these mitigation concepts. They included the use of a large sand fill around the fuel tank and fuel cell bay, placement of blasting mats over the roof and walls of the fuel cell building, use of a thick steel liner plate over the roof and concrete walls of the fuel cell building, and installation of a high

strength fiber wrap around the building walls. The steel plate, fiber wrap, and blasting mats were all intended to be used with sand fill inside the fuel cell bay around the fuel tank.

Fragment and building debris predictions were made for the “baseline” mitigation case where the fuel cell bay was filled with sand around the fuel tank. The Otto fuel explosion was assumed equivalent to 630 lbs of TNT. Sand and concrete penetration equations[6][3] were used to determine that the primary fragments from the fuel tank would not penetrate through a sand fill around the charge inside the fuel cell bay and the concrete walls of the bay. The sand fill height in the bay above the fuel cell was sufficient to substantially slow the top head fragment from the tank. There was uncertainty in the calculated results, however, because the sand penetration equations were not developed for a sand mass that was also subject to blast pressures from a buried explosion. The velocity of concrete debris from the walls of the fuel cell bay was calculated to be 600 ft/sec using the Gurney equation for a cylindrical cased charge, where the casing weight included the weight of the fuel tank, sand fill inside the fuel cell building, and the concrete walls of the building. This approximate debris velocity calculation indicated that building debris would be a hazard to the surrounding occupied areas, unless the mitigation system included material outside the bay that substantially slowed the wall debris velocity.

Testing Program

There were no adequately validated methods available that would predict the blast and building debris hazard reduction provided by any of the mitigation concepts under consideration for this application. Therefore, a two phase test program was initiated for this purpose. The first phase of the test program was a screening study, where each concept was modeled in an approximate manner with small scale experiments using available materials. The most promising concept was tested in a more accurate manner at a larger scale in the second phase of the test program.

Initial Test Series

A scale factor of 1:4.8 was chosen for the initial phase of the test program. This scale allowed the fuel cell bay to be modeled in an approximate manner with available reinforced concrete pipe. Since the building was overwhelmed by the internal blast pressures, only the thickness and density of the building walls and the charge standoff to the walls of the bay were considered important parameters for the first testing phase. Replica scaling was used to scale the materials, although all relevant dimensions were not scaled exactly, and Hopkinson-Cranz scaling was used to model the explosive. The scaling procedure did not scale gravity forces, which were assumed to be negligible. In all the tests, sand fill, with some clay content, was used around the charge inside the concrete pipe to simulate sand fill around the fuel tank inside the fuel cell bay. The basic, or baseline setup for the tests without any mitigation material outside the concrete pipe is shown in Figure 2. It models a 630 lb TNT detonation in the fuel tank, surrounded by the reinforced concrete bay filled with sand.

The tests also included materials that were placed outside the reinforced concrete pipe to slow concrete debris from the pipe and/or strengthen the pipe, as shown in Table 2. The table shows the dimensions used in the scaled tests, which can be converted to the full scale dimensions by

multiplying by the scale factor of 4.8. Some of the full scale dimensions represent very substantial strengthening measures. However, the intent during this phase was to model mitigation concepts with readily available materials, even if they did not represent feasible full scale values, and then judge the effectiveness of the concepts based on the amount of material used in the tests.

Table 3 shows the test matrix for the initial phase of the test program. All tests shown in Table 3 were conducted with a 5.67 lb cylindrical TNT charge, with a length-to-diameter ratio of 2, in the "baseline" setup shown in Figure 2. This setup was supplemented with additional mitigation techniques in most of the tests as shown in the test matrix. However, the steel fuel tank itself was not modeled in all the tests with a steel pipe placed around the charge since direct comparison tests showed that the steel pipe did not affect external blast pressures and it was not considered necessary to model primary fragments from the fuel tank during every test in this phase.

Table 2. Mitigation Concepts

Mitigation Concept	**Description (with dimensions used in scaled tests)**
Baseline Sand Fill Around Charge Inside Concrete Pipe	6.5 inch radius of sand around charge and 29 inches of sand over charge (scaled sand + concrete cover around charge = 0.42 ft/lb$^{1/3}$)
Additional 3.3" Sand Fill Around Concrete Pipe	Uniform 3.3 inch sand thickness around outside of concrete pipe (scaled sand+concrete+sand cover around charge = 0.59 ft/lb$^{1/3}$)
Additional 6.5" Sand Fill Around Concrete Pipe	Uniform 6.5 inch sand thickness around outside of concrete pipe (scaled sand+concrete+sand cover around charge = 0.73 ft/lb$^{1/3}$)
Steel Pipe Around Concrete Pipe	26 inch O.D. steel pipe (0.5 inch wall thickness) around concrete pipe. Steel pipe is 34 inches high with an open top and bottom.
Steel Blasting Mats Around Concrete Pipe	2 ft square blasting mats constructed with 0.5 inch diameter steel wire rope tied together to form a box around and over the concrete pipe
High Strength *Carbon* and *E-glass* Fiber Wrap Around Concrete Pipe	High strength *carbon fiber* strands (12 kips/inch tensile hoop strength) and *E-glass* strands (7.5 kips/inch tensile hoop strength) in a resin-based wrap epoxied to concrete pipe

Table 3. Initial Test Matrix

Test No.	Fuel Tank Fragments Simulated?	Mitigation Concept
1	No	Baseline Interior Sand Fill (6.5 inch radius of sand around charge, 29 inches of sand over charge inside concrete pipe) - No Material Outside Concrete Pipe
2	Yes	Baseline Interior Sand Fill No Material Outside Concrete Pipe
3	No	Baseline Interior Sand Fill + Additional 6.5 inch Thick Uniform Sand Fill Around Outside of Concrete Pipe
4	No	Baseline Interior Sand Fill + Additional 3.3 inch Thick Uniform Sand Fill Around Outside of Concrete Pipe
5	Yes	Baseline Interior Sand Fill + 6.5 inch Sand Fill Around Pipe Toward Gauges 0 inch Sand Thickness Around Concrete Pipe on Side Opposite Gauges
6	Yes	Baseline Interior Sand Fill + Carbon Fiber Wrap Around Outside of Concrete Pipe
7	Yes	Baseline Interior Sand Fill + Steel Pipe Around Outside of Concrete Pipe
8	No	Baseline Interior Sand Fill + Blasting Mats Around Outside of Concrete Pipe
9	No	Baseline Interior Sand Fill + Blasting Mats Around Outside of Concrete Pipe
10	No	Baseline Interior Sand Fill + E-glass Fiber Wrap Around Outside of Concrete Pipe

Data collection during the tests included blast measurements, video tape, still photography, and debris collection. Free-field blast pressure histories were measured using PCB piezoelectric pressure transducers that were installed in pencil gauges on a radial line from the charge. Pressures were measured at scaled distances representing the control room, the parking lot, the administration building, and an additional intermediate point. Debris was collected after the tests around the explosion site and maximum distances of observed debris throw were noted. The furthest distance that primary fragments from the steel pipe around the charge were observed was also noted.

Results from the Initial Test Series

Table 4 shows measured reductions in peak free-field pressures and impulses from each test relative to "reference" peak pressure and impulse values calculated at the same scaled standoffs from an unmitigated hemispherical surface burst of 5.67 lbs TNT. Budget limitations precluded baseline pressure measurements for an unmitigated cylindrical burst. Cases where the measured pressure histories appeared to be affected by drift or ringing of the gauge are marked with "N/A" in Table 4. Figures 3 and 4 show pressure histories measured at scaled distances of 4.8 ft/lb$^{1/3}$ and 25.1 ft/lb$^{1/3}$ for Test 4. Multiple pulses, with the peak pressure occurring some time after the

shock wave arrival time, were typically measured at the scaled distance of 4.8 ft/lb$^{1/3}$. In tests with the highest mitigation factors, multiple pulses were also measured at a scaled stand-off of 25 ft/lb$^{1/3}$. Peak pressures measured at the furthest scaled stand-off, equal to 70 ft/lb$^{1/3}$, were consistently less than the resolution of the measuring system and are not reported. These pressures were always less than 0.1 psi. Video tapes of the tests showed that the fireball, and presumably the blast pressures, initially vented out the bottom of the reinforced concrete pipe and sand fill in each test.

Very significant reductions in the peak blast pressure and impulse were measured during all the tests. At the closer-in scaled standoffs, the peak blast pressures were mitigated more than the impulses. However, measured peak pressure reduction factors decreased significantly with scaled standoff for each test, while measured impulse reduction factors were only slightly affected by scaled standoff. Therefore, in most cases at the larger scaled standoffs the peak blast pressures and impulses were mitigated by approximately equal amounts.

Table 4. Blast Pressure Reductions Measured at Given Scaled Standoffs Z in ft/lb$^{1/3}$

Test No.	Peak Pressure Reduction Factor (P_{ref}/P)			Impulse Reduction Factor (I_{ref}/I)		
	Z= 4.8*	Z = 11.35	Z = 25.3	Z = 4.8	Z = 11.35	Z = 25.3
1	21.3	5.2	3.3	4.6	4.4	3.5
2	22.1	N/A	3.6	4.6	N/A	3.6
3	62.8	N/A	11.9	6.7	N/A	5.6
4	33.5	N/A	6.1	5.0	N/A	5.0
5	50.3	N/A	13.4	7.1	N/A	10.3
6	22.1	4.7	3.5	5.8	4.2	3.1
7	34.6	10.8	6.0	11.1	8.1	6.2
8	55.3	18.9	8.6	7.0	6.8	5.8
9	27.7	8.4	6.5	6.7	7.8	6.2
10	70.9	17.2	14.3	10.0	9.2	7.6

*Z = scaled standoff with units of ft/lb$^{1/3}$

A comparison of Tests 1 and 2 shows that the steel pipe casing around the charge, that modeled the fuel tank, did not significantly affect the measured blast pressures. This is probably due to the fact that any attenuation provided by the 1/4 inch thick pipe was small compared to that provided by the 9 inch radius of sand and concrete around the charge and steel pipe. A comparison of Tests 3, 4, and 5 to baseline Tests 1 and 2 shows that the measured reductions in blast pressures increased with the amount of sand fill around the sides of the charge. The sand cover over the top of the charge was fixed in all these tests at 29 inches, 10 inches greater than the largest thickness of sand and concrete pipe around the sides of the charge. A comparison of Test 5 with Tests 3

and 4 also shows that the measured blast pressures were dependent to a large extent on the thickness of cover on the side of the charge facing the blast gauges, rather than on the average thickness of cover.

A comparison of Tests 6 and 10 to baseline Tests 1 and 2 shows that the effectiveness of high strength wrap around the concrete pipe was dependent on the ductility of the wrap. The E-glass fiber wrap used in Test 10 has less tensile strength the carbon fiber wrap used in Test 6, but it absorbs approximately 300% more strain energy prior to failure. Results from Test 10 show that it was very effective in reducing blast pressures. The less ductile carbon fiber wrap used in Test 6 provided virtually no additional mitigation of the blast pressures compared to the baseline case in Tests 1 and 2.

A comparison of Test 7 and Test 1 shows that the steel pipe placed outside the concrete pipe in Test 7 caused significant mitigation of both peak pressure and impulse. Finally, results from Tests 8 and 9 show the effectiveness of the blast mats for reducing external blast pressures. The blast pressure reductions measured in Test 8 are more or less equal to those measured during Test 3 with the largest total amount of sand fill around the charge. However, it must be noted that the blasting mats were nearly full scale mats (a 0.75 inch wire diameter is the largest available size compared to the 0.5 diameter used in the tests). The wire cable connections holding the mats in a box shape around the charge failed during Test 8, whereas the stronger, shackled connections used in Test 9 did not fail. It is hypothesized that higher blast pressures were measured during Test 9 because the shackles left more of a gap between the mats at the corners where they were connected together.

All the techniques slowed the primary fragments to the extent that none were observed at distances greater than that of the concrete pipe debris. Since gravity forces were not modeled, measure debris throw distances cannot be scaled up to full-scale values. However, none of the mitigation concepts reduced the debris throw from the reinforced concrete pipe that modeled the fuel cell bay to distances that were considered acceptable. In all tests, the smallest pieces of debris (1.5 inch maximum dimension) were thrown the furthest distances. This debris was apparently thrown from the concrete pipe section nearest the charge. The top several inches of the concrete pipe typically held together to form a large ring of concrete that was found near the explosive site. Debris throw was observed at distances greater than 300 ft for Tests 1 and 2, which had the minimum level of mitigation. The debris throw distances were reduced so that almost all of the debris was within 150 ft of the explosion site for Test 3, where 6.5 inches of additional sand was placed around the outside of the concrete pipe. Debris from the concrete pipe inside the steel pipe in Test 7 was observed at distances up to about 100 ft from the explosion. In Tests 8 and 9, the blasting mats mitigated the debris hazard by reducing the maximum observed debris throw distance to approximately 50 ft. This debris seemed to be thrown primarily out the corners, where the mats were joined together. However, in Test 8 the mats also became debris and were thrown distances as far as 600 ft because they were not adequately secured together. The mats showed no significant damage after Test 8, but they did suffer significant damage during Test 9. The high strength fiber wraps used in Tests 6 and 10 did not significantly reduce the concrete pipe debris throw distances compared to the baseline Tests 1 and 2.

The 26 inch diameter steel pipe used in Test 7 had the interesting effect of creating a very large additional piece of debris, since it was thrown approximately 60 ft almost straight up into the air. The diameter of the steel pipe enlarged at the base (near the charge), so that it had a permanent strain of approximately 18 percent, while there was no permanent deformation near the top. This “bell” shape may have provided a surface for the sand to apply upward loads to the steel pipe, as it was thrown outward in contact with the pipe, and upward, out the open top of the pipe.

In summary, in all the tests the peak blast pressures at all scaled distances representing inhabited areas around the fuel tank were mitigated to acceptable levels. The mitigation approaches also seemed to slow primary fragments so that they were not thrown any further than the general building debris. However, none of the mitigation concepts reduced concrete debris throw distances to acceptable limits. Therefore, a configuration where the fuel tank was located outside the fuel cell bay in a large sand fill, or berm was identified as the candidate suppression system that would be tested in the second, final phase of the testing program.

Second Test Series

The sand berm suppression system was tested at one-third scale, which was considered the largest feasible scale that could be used for the tests. Figure 5 shows the typical sand configuration used around the charge for these tests. The test layout is shown in Figure 6. Replica scaling was again used to determine the dimensions of all materials and Hopkinson-Cranz scaling was used to scale the charge weight. The fuel tank was modeled in each test with an 8 inch diameter by 18 inch long steel pipe, with one-half inch thick walls. One-half inch thick steel plates were placed on the top and bottom of the pipe to simulate endcaps on the fuel storage tank. A cylindrical charge of C4 explosive was placed in the central portion of the steel pipe, with a detonator at one end. A cardboard tube, which was just large enough to fit around the steel pipe, was placed around the steel pipe to simulate a fiberglass vault surrounding the fuel storage tank inside the sand berm that would permit periodic inspection of the tank.

A total of four tests were performed with 20.5 lbs of C4. Using a TNT equivalency factor of 1.13 based on a ratio of the heats of detonation, this charge weight represents a full scale TNT charge weight of 630 lbs. One additional one-third scale test was performed with a charge weight of 40.5 lbs of C4, representing a full scale TNT charge weight of 1240 lbs. A variety of diameters and heights of sand were used around the charge to determine the smallest sand berm configuration that provided adequate protection. Table 5 shows the test matrix that was used with scaled dimensions of sand fill. Full scale dimensions can be obtained by multiplying these values by the scale factor of 3. The sand thickness around the charge was uniform in each test.

Table 5. Second Test Series Matrix

Test No.	Equivalent TNT Charge Weight (lb)	Dimensions of Sand Containment		
		Diameter (ft)	Total Height (ft)	Scaled Sand Cover Around Sides of Charge (ft/lb$^{1/3}$)
11	23.2	5	4.3	0.88
12	23.2	4	5	0.70
13	23.2	4	5	0.70
14	23.2	6	6	1.05
15	45.8	10	6.7	1.4

Side-on (free-field) blast gauges were mounted on a radial line at the same scaled distances used for the initial test series. The closest gauge represented the minimum distance to the occupied control room. Witness panels were placed around the test systems to determine if primary fragments from the simulated fuel storage tank were escaping with sufficient velocity to penetrate the 12 inch thick concrete walls of buildings around the proposed fuel tank location that blocked line-of-site fragment trajectories toward inhabited areas. These witness panels were placed at approximately a 5 ft standoff from the edge of the sand fill. Two of the witness panels consisted of small precast vaults with 2-1/2 inch thick concrete walls and a 0.75 inch layer of plywood on the outside face of the walls. Three other witness panels consisted of fiberglass pipe with 0.5 inch thick walls filled with soil. Following each test, primary fragments from the steel pipe were picked up around the test area.

Results from Second Test Series

Table 6 shows measured reductions in peak free-field pressures and impulses from each test relative to "reference" peak pressure and impulse values calculated at the same standoffs from a hemispherical surface burst equal to the TNT charge used in each test. In all cases, the blast pressures were mitigated below the permissible levels shown in Table 1. Also, the blast load measured at the simulated control room location were always below the blast capacity of the roof and walls.

Table 6. Summary of Measured Blast Pressures from Second Test Series

Test No.	Pressure Reduction Factor (P_{ref}/P)			Impulse Reduction Factor (I_{ref}/I)		
	R = 12.7 ft	R = 32 ft	R = 72 ft	R = 12.7 ft	R = 32 ft	R = 72 ft
11	125.7	25.2	15.4	9.2	8.6	7.3
12	55.3	9.5	8.6	7.5	6.3	6.2
13	46.1	N/A	5.4	6.9	N/A	6.2
14	212.7	N/A	28.7	15.0	N/A	124.0
15	404.0	86.0	62.0	29.6	N/A	N/A

Figures 7 and 8 show plots of the peak pressure and impulse reduction factors that were measured during tests in both test series where only sand fill, or sand fill plus the reinforced concrete pipe, were used around the explosive. The reinforced concrete pipe in the initial test series is considered equivalent to an equal thickness of sand, since the pipe was overwhelmed by the blast loads and its density is not much greater than that of sand. The two figures show that the measured reduction factors are a function of the radius of sand fill around the explosive facing the blast gauges (T) scaled by the cube root of the equivalent TNT charge weight (W). In all cases but one, the sand thickness was uniform around the sides of the charge. Also, the height of sand above the charge was greater than T in all the tests. The plots show that the data from both test series can be characterized with the same relationships, indicating that the results from the two series both follow the replica scaling law used to set up the tests.

The gauges in Test 15, which had the largest amount of scaled sand thickness around the charge, were at somewhat smaller scaled distances than the other tests. Despite this, the data points in Figure 7 from this test are slightly below the line formed by the other data points at smaller scaled sand thicknesses. This indicates that the mitigation provided by the sand may level off at larger scaled sand thicknesses around the charge. Prediction curves for peak pressure and impulse mitigation caused by a surrounding earth fill can be developed by curve-fitting through the data in the plots in Figures 7 and 8. However, the curve-fit may not be accurate outside the limits of the data in the plots.

A small number of fragments from the steel pipe around the charge impacted the 3/4 inch plywood witness panels, but no fragments penetrated completely. Some fragments from the pipe were located at the base of the fiberglass pipe witness panels, but no penetrations were observed. Primary fragments were located at a maximum distance of approximately 150 ft from the charge and most fragments were located within 50 ft of the charge. This was equal to the average range of sand dispersal. This indicates that fragments from the Otto fuel tank would be sufficiently slowed by the sand so that they would not represent a significant hazard to nearby inhabited areas of the plant. The weight of the primary fragments collected in the tests ranged from 35% to 50% of the weight of the steel pipe around the charge.

Summary and Conclusions

Several concepts were studied that would mitigate the potential fragment, debris, and overpressure hazards from an Otto fuel tank explosion in a reinforced concrete bay assumed equal to 630 lbs of TNT. The concepts included placing large amounts of sand fill around the tank storing the Otto fuel and around the walls of the bay, strengthening the walls of the bay with steel plate or with high strength fiberglass wrap, and placing blasting mats outside the walls of the bay. An initial test program was conducted at 1:4.8 scale to investigate the effectiveness of each of these concepts. In all cases, blast overpressure hazards were mitigated by substantial amounts but the throw distances of debris from the reinforced concrete walls of the bay were not reduced to an acceptable distance. The effect of a large sand berm (minimum 12 ft diameter) around the fuel tank outside the bay was investigated in a second test series conducted at 1:3 scale. These tests showed that this system reduced blast overpressures at nearby occupied areas well below permissible levels, and slowed primary fragments from the fuel tank so that throw distances were approximately equal to the distance of sand dispersal. Plywood witness panels showed that primary fragments did not penetrate more than 0.75 inch. This testing demonstrated that the suppression system would provide adequate protection to surrounding inhabited areas. Construction of a 12 ft diameter sand berm suppression system around the Otto fuel tank was accomplished quickly and allowed surrounding plant operations to continue with minimal delays.

Plots of the measured peak pressure and impulse reduction factors, as compared to peak pressures and impulses from an unattenuated surface burst of the same charge weight, showed that the reduction factors were a function of the scaled sand radius around the charge. Peak pressure reduction factors were also a strong function of the scaled distance from the charge.

References

1. “Ammunition and Explosives Safety Standards,” U.S. Department of Defense, DoD 6055.9-STD, Change No. 3, January 1991.

2. “Prediction of Building Debris for Quantity-Distance Siting,” Department of Defense Explosives Safety Board Technical Paper No. 13, April 1991.

3. “Structures to Resist the Effects of Accidental Explosions,” Department of the Army Technical Manual TM5-1300, Department of the Navy Publication NAVFAC P-397, Department of the Air Force Manual AFM 88-22, Revision 1 dated 19 November 1990.

4. Baker, W.E. and Westine, P.S., “Methods of Predicting Blast Loads Inside and Outside Suppressive Structures,” EM-CR-76026, Report No. 5, Edgewood Arsenal, Aberdeen Proving Ground, Maryland, 1975.

5. Polcyn, M.A., Marchand, K.A., and Oswald, C.J., “Development, Fabrication, and Proof Testing of a Container for On-Site Munition Demolition,” Southwest Research Institute Project No. 06-6827, Contract No. 87-93-D-0016, Delivery Order 0005, Prepared for Department of the Army, U.S. Army Engineering and Support Center, Huntsville, Alabama, December 1995.

6. “A Manual for the Prediction of Blast and Fragment Loading on Structures,” DOE/TIC-11268, Prepared by Southwest Research Institute for the U.S. Department of Energy, Albuquerque Operations Office, July 1992.

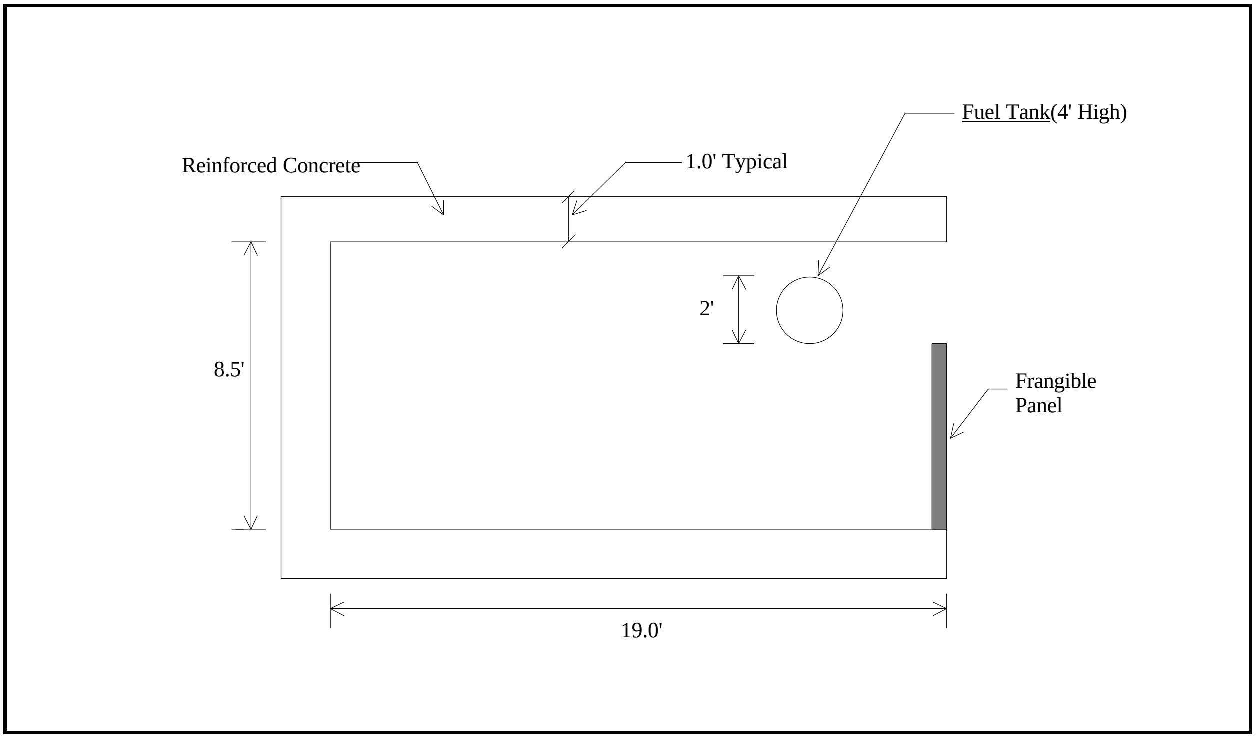

Figure 1. Layout of Otto Fuel Cell and Surround Reinforced Concrete Bay

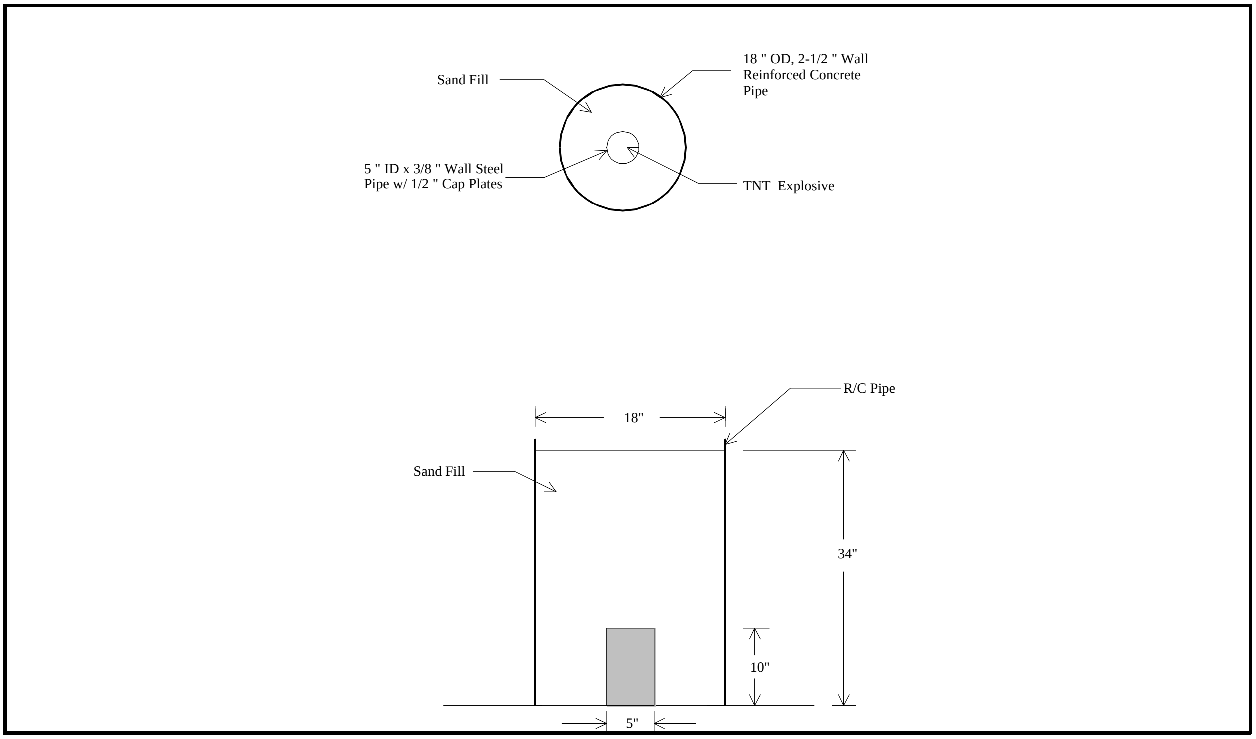

Figure 2. Basic Cross Section for Explosive Inside Sand-Filled Reinforced Concrete Pipe in 1:4.8 Scale Tests

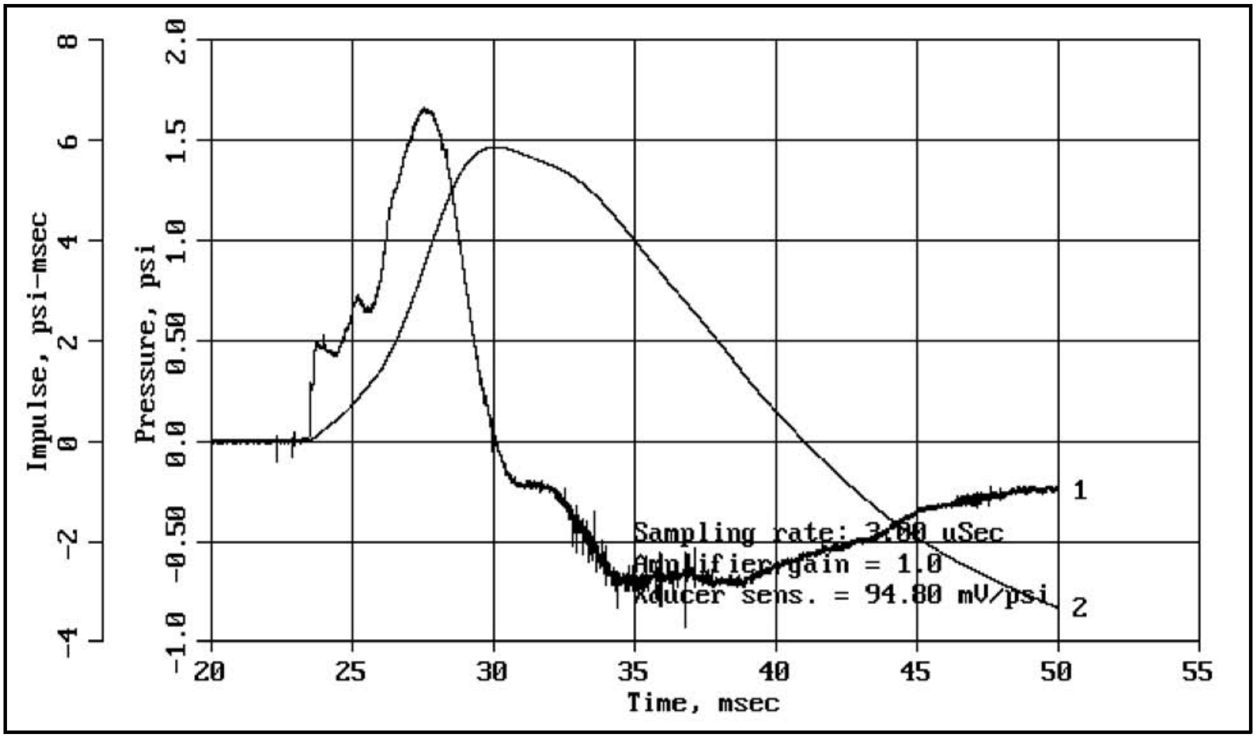

Figure 3. Typical Measured Pressure History at a Scaled Distance of 4.8 ft/lb$^{1/3}$

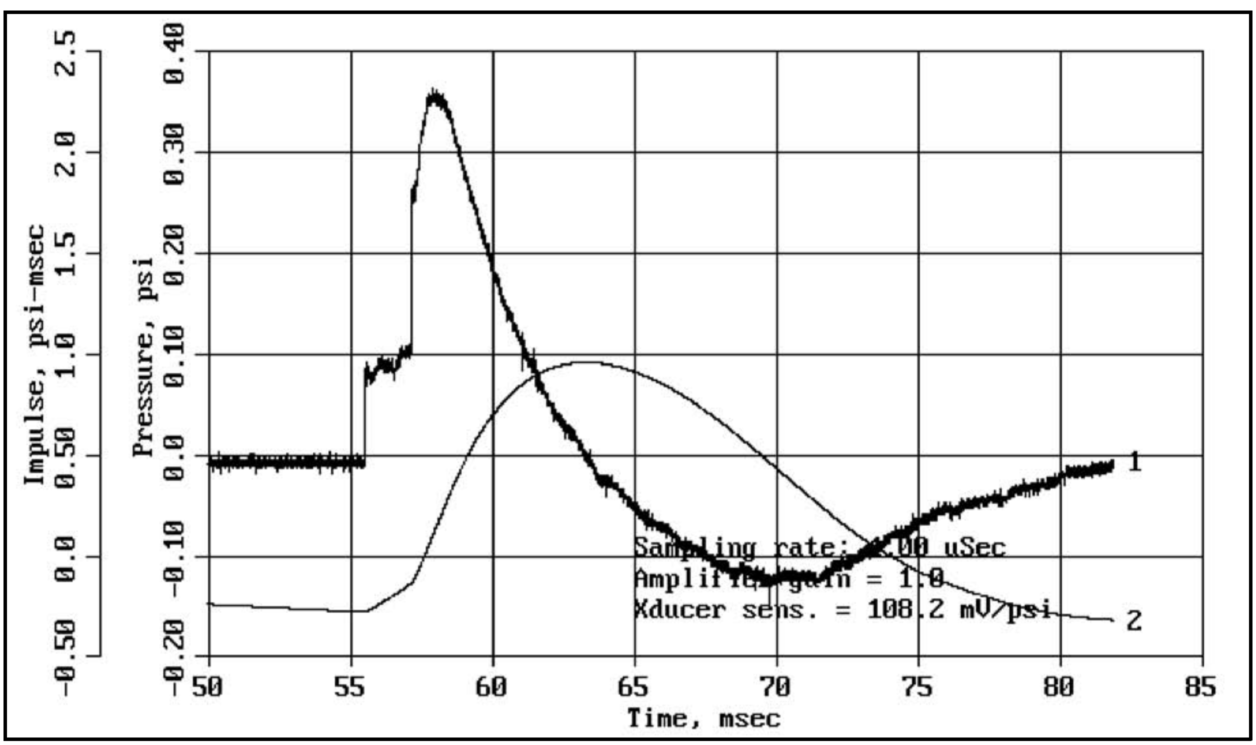

Figure 4. Typical Measured Pressure History at a Scaled Distance of 25.1 ft/lb$^{1/3}$

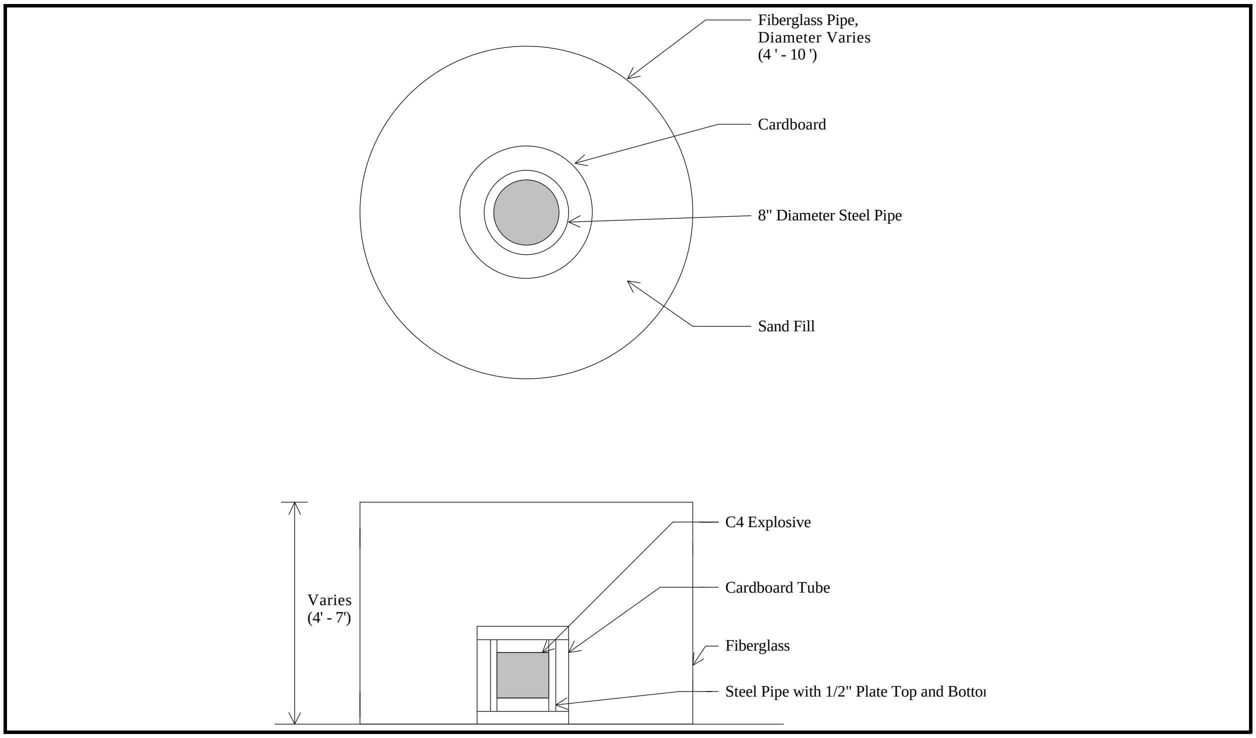

Figure 5. Typical Configuration of Explosive in Sand Fill in 1:3 Scale Tests (Not to scale)

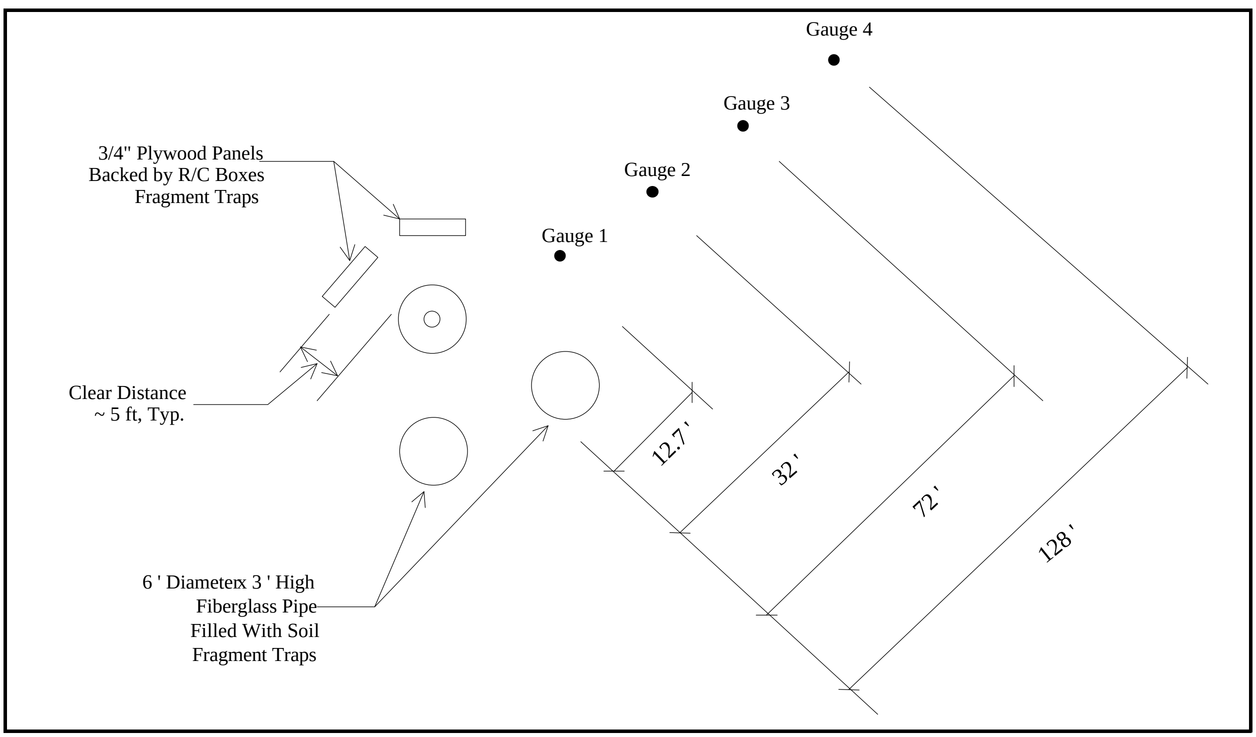

Figure 6. Layout of 1:3 Scale Tests

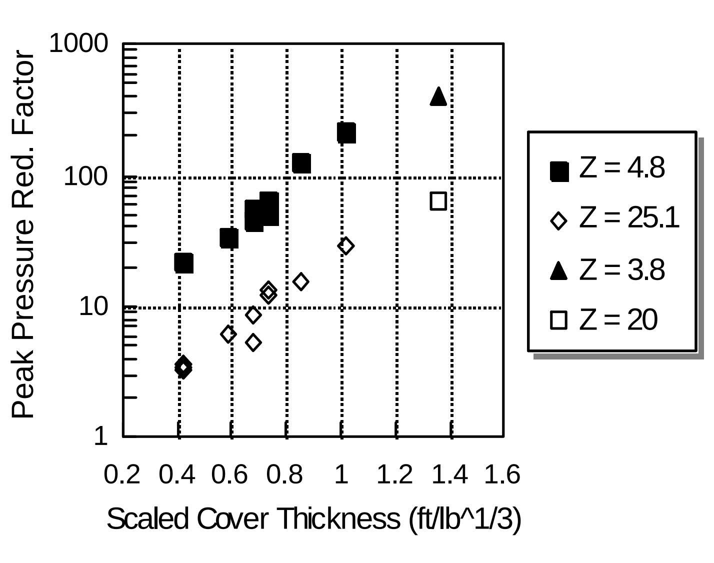

Figure 7. Plot of Scaled Radius of Sand Cover vs. Peak Pressure Reduction Factor

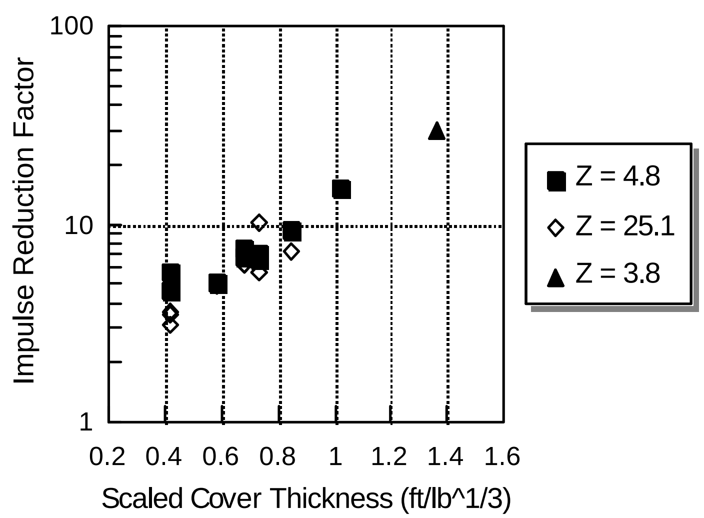

Figure 8. Plot of Scaled Radius of Sand Cover Around Charge vs. Impulse Reduction Factor